Progressive Collapse Analysis of Reinforced Concrete Buildings

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Abstract. The progressive collapse of multi-story buildings has attracted the attention of structural engineers in the recent past. Progressive collapse is initiated by the sudden loss of vertical load carrying key elements. It causes a series of failures that lead to the partial or total collapse of a structure. In the present study, different factors that influence the progressive collapse resistance capacity of a structure are investigated. The factors include the nature of the event causing the loss of a key element, structure properties such as span length, member sizes (beam and column), and location of column removal. A nonlinear time history analysis of the building is performed for the progressive collapse using Etabs 2020 software. The response quantities include the number of plastic hinges formed, vertical displacement, and rotation of joints. The findings reveal that increasing beam depth and reducing grid span enhance structural robustness, effectively resisting bending moment and shear force.

Keywords: Progressive collapse; RC building; Nonlinear time history analysis

1 Introduction

Progressive collapse, a phenomenon observed in structural engineering, refers to the disproportionate collapse of a particular portion of a building due to the localized failure of a specific element. Notable incidents such as the Ronan Point tower block (London) collapse in 1968 and the Oklahoma City bombing in 1995 have drawn attention to the risks associated with progressive collapse. Natural disasters, including earthquakes and hurricanes, and human-induced events like explosions and terrorist attacks, can trigger progressive collapse by causing the initial failure or loss of critical structural elements. Increased awareness has led to the development of codes [1,2] and ensuring structural integrity against progressive collapse. Despite these measures, progressive collapse remains a significant concern. As a result, ongoing research is

needed to understand the mechanisms of progressive collapse further and to develop more effective design strategies to prevent it.
Nyunn et al., 2019 [3] investigated the effect of external masonry walls on a building's resistance to progressive collapse. Shayanfar and Javidan, 2017 [4] observed that incorporating shear walls into the building design significantly enhanced its resistance to progressive collapse. Panahi and Zahrai, 2021 [5] evaluated retrofitting techniques such as column ties, shear walls, and post-tensioning systems to enhance the resistance of concrete buildings against progressive collapse. Similarly, Azim et al., 2019 [6] underscored the effect of design, construction, materials, and loading on the resistance of reinforced concrete (RC) frame structures against progressive collapse. Yousef et al., 2020 [7] compared different methods for simulating progressive collapse in high-strength concrete frame buildings. They suggested nonlinear dynamic analysis as the most accurate method for ensuring safety and resilience against extreme loads. Gowtham et al., 2018 [8] emphasized that while 2D linear static analysis is straightforward, it may not capture the complex behavior associated with progressive collapse. On the other hand, non-linear dynamic analysis provides accurate results at the expense of computational intensity. The choice of analysis method depends on the characteristics of the building and its anticipated use. Similarly, Mahmoud et al., 2018 [9] explored various methods, including alternate path analysis, direct design, and nonlinear dynamic analysis, to enhance the safety of steel structures under seismic loads. They advocated for a combination of these approaches to improve the overall safety of such structures.

The available literature shows that the behavior of structures under progressive collapse conditions is widely studied in recent years. While the mentioned studies address the impact of column removal and load transfer on progressive collapse resistance, there is a research gap specifically in examining the effect of varying beam size and grid size. Understanding how these factors influence structural behavior during progressive collapse is crucial for optimizing building design and mitigating the risk of collapse. Additionally, the literature review focuses on nonlinear dynamic analysis to assess the location of column removal. It allows for a more detailed and accurate assessment of the dynamic response of structures under extreme loads, making it essential to explore its application in studying the progressive collapse behavior associated with column removal.

With the abovementioned gap areas identified in the available literature, the objectives of the present study are (1) to analyze the effect of peripheral beam size on progressive collapse resistance, (2) to analyze the effect of grid/span size on progressive collapse resistance, (3) to study the effect of the location of column removal on progressive collapse resistance.

2 Modelling of the Building

A fixed base 3-Dimensional frame model of a seven storey building is created using Etabs software. Line elements are used to model columns and beams, and slabs are modeled as shell elements. Appropriate gravity loads, including dead and live loads, are applied to the structure. The building is designed for gravity and earthquake loads as per IS 456:2000. Nonlinear deformation in the structure caused during progressive collapse is considered by providing hinges at beam and column ends. Nonlinear dynamic analysis is performed to study the progressive collapse behavior of the building.

3 Numerical Study

A Reinforced concrete building is considered for the analysis. Fig. 1 shows the 3-D model of the 7-storey building. The building has plan dimensions of 30 m x 30 m with equal grid sizes of 6m x 6m. The height of the building is 21 m, with each storey of height 3 m. The beam size considered is 300 x 500 mm, slab thickness 200 mm, and column size 500 x 500 mm is considered. The grades of concrete are M25 and steel reinforcement bars Fe500, respectively. The building is designed for combinations of gravity loads and earthquake loads for Zone V (IS 1893: 2016) as per Indian standards. Reinforcement is provided conforming to IS 13920: 2016 with the help of the ductile detailing option in ETABS. Beam reinforcement thus obtained is 1.1% at the top face and 0.55% at the bottom face of the section, and maximum column reinforcement is 2.9%

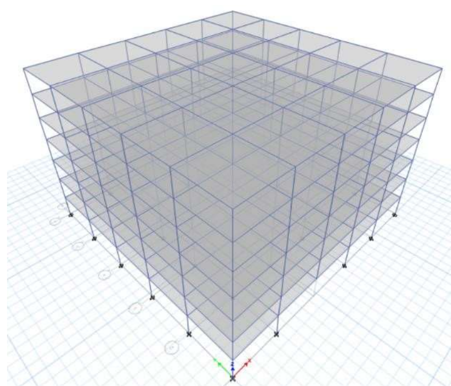


Fig. 1. 3-D Model of the building

4 Procedure for Nonlinear dynamic analysis of building under progressive collapse scenario

- The specific element (column) that will be failed to initiate the progressive collapse scenario is identified, and axial force being carried by the column is noted.

- The considered column is removed, and axial force is applied at the joint in an upward direction.
- Ramp function is created for the applied axial load, as shown in Fig. 2, which simulates sudden column removal.
- The analysis settings are configured to perform a nonlinear dynamic analysis for progressive collapse. Time history analysis of the building is performed by using the direct time integration approach in ETABS. Rayleigh mass and stiffness proportional damping is used with the critical damping value as 5%. The structure's nonlinear behavior during progressive collapse is taken into account by providing plastic hinges near the ends of beams and columns.
- The analysis is performed to study three conditions, namely (1) the effect of peripheral beam size, (2) the effect of grid size, and (3) the effect of location of column removal.
- While studying the effect of peripheral beam size on the response of the structure under progressive collapse conditions, a check for the column-beam capacity ratio is also performed to ensure strong column-weak beam condition at each joint.
- The deflection values and number of hinges are examined to obtain the overall behavior of the structure

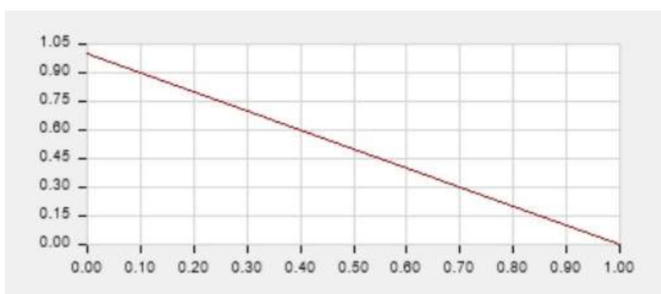
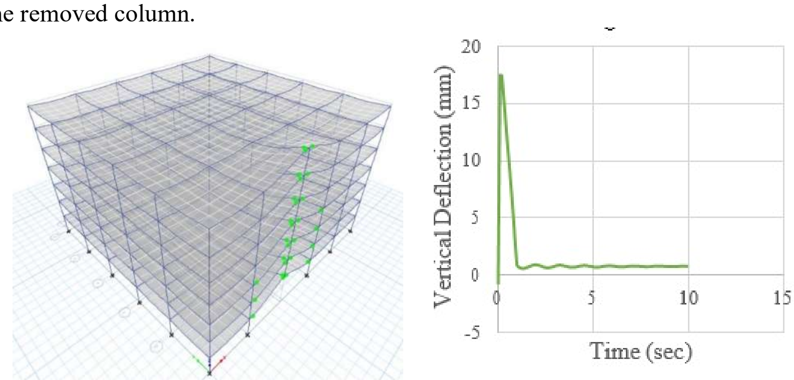


Fig.2. Ramp Function Graph

5 Discussion of the Results

For the building frame, two response quantities of interest are evaluated: vertical deflection at the point of column removal and the number of plastic hinges formed. The effect of beam size, grid size and column location variation on these quantities are investigated.

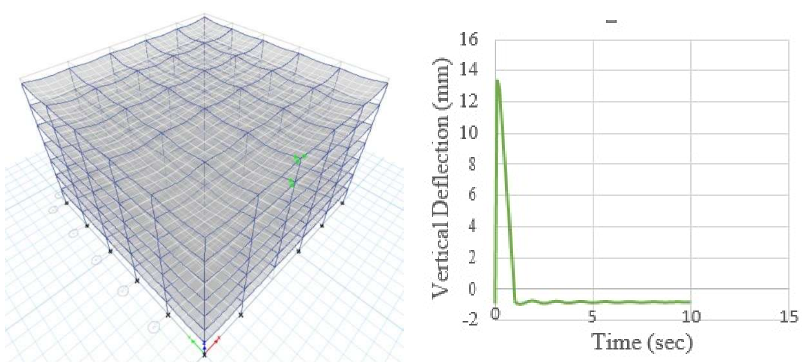
Fig. 3 shows the number of hinges formed and vertical deflection at the column removal point when peripheral beam sizes are 300 x 500 mm. The figure indicates that the sudden removal of a column in the lower storey results in damage to adjacent beams, which propagates upwards, affecting the section of the building directly above the removed column.



(a) (b)

Fig. 3. Case 1: Middle column removal, peripheral beam 300 x 500 mm, grid size 6m x 6m (a) Hinges formed in the structure; (b) Vertical deflection at the column removal location

Fig. 4 shows the number of hinges and vertical deflection at the column removal point for 300 x 600 mm peripheral beam size. The results demonstrate that increasing the peripheral beam size leads to a notable decrease in the number of hinges formed, indicating reduced structural damage.



(a) (b)

Fig. 4. Case 2: Middle column removal, peripheral beam 300 x 600 mm, grid size 6m x 6m (a) Hinges formed in the structure; (b) Vertical deflection at the column removal location

Fig. 5 shows the column-beam capacity ratios of the peripheral frame of the building, when peripheral beam sizes are 300 x 600 mm. The figure shows that column-beam capacity ratios are equal to and more than 1.4, satisfying the code recommendations.

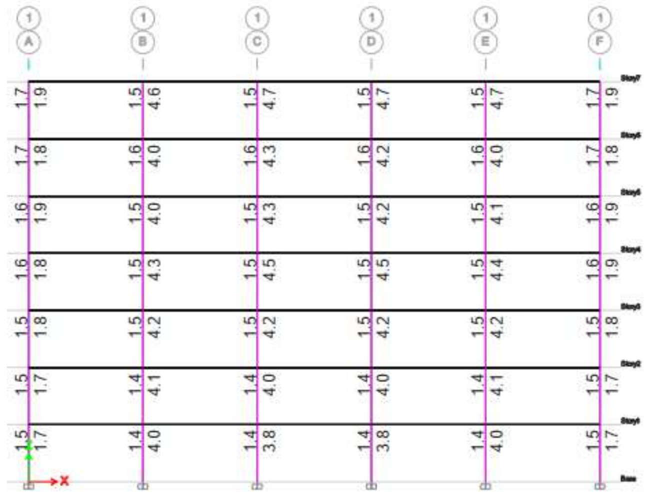
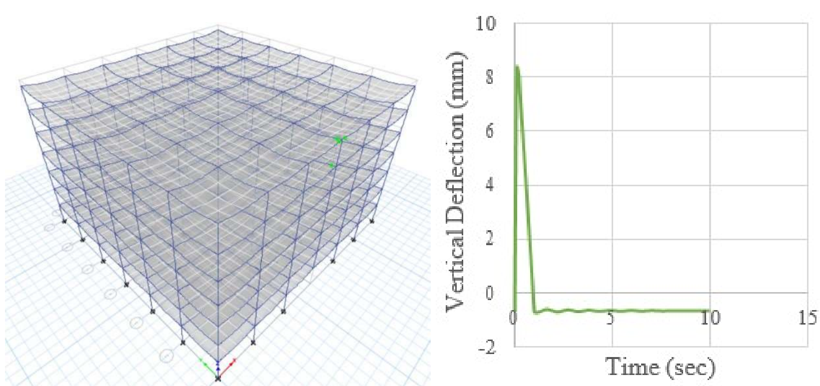


Fig. 5. Column-Beam capacity ratios for peripheral beam sizes are 300 x 600 mm, grid size 6m x 6m

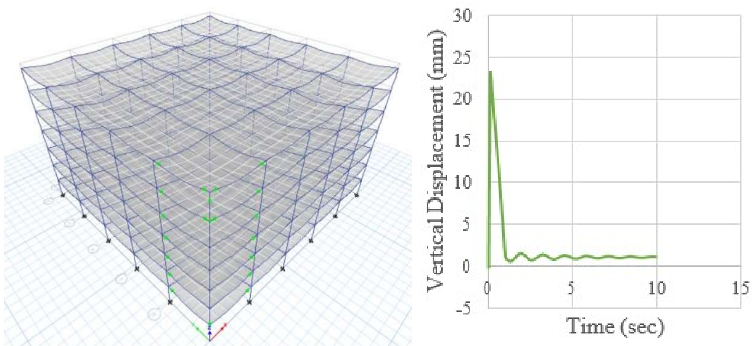
Fig. 6 shows the number of hinges formed and vertical deflection at the column removal point when peripheral beam sizes are 300 x 500 mm, and grid size is changed to 5m x 5m. The figure, compared with Fig. 3, illustrates that as the grid size decreases from 6m to 5m, the number of hinges decreases by 85%, and there is a reduction of over 50% in vertical deflection.



(a) (b)

Fig. 6. Case 3: Middle column removal, peripheral beam 300 x 500 mm, grid size 5m x 5m (a) Hinges formed in the structure; (b) Vertical Deflection at the column removal location

Fig. 7 shows the number of hinges formed and vertical deflection at the column removal point when peripheral beam sizes are 300 x 500 mm, the grid size is 6m x 6m, and the corner column is removed instead of the middle column. From the figures, it can be surmised that middle column removal from the periphery of the building causes maximum hinge formation, and corner column removal causes maximum vertical displacement in the structure.



(a) (b)

Fig. 7. Case 4: Corner column removal, peripheral beam 300 x 500 mm, grid size 6m x 6m (a) Hinges formed in the structure; (b) Vertical Deflection at column removal location

6 Conclusions

The results indicate that increasing beam depth and decreasing span length can enhance the resistance to progressive collapse. Deeper beams improve structural robustness against bending moment and shear forces, while smaller grid sizes offer better insight into local behavior, enhancing resistance. Removing a corner column is the most critical failure scenario, resulting in maximum deflection, while interior column removal leads to minimal failure. Employing design strategies like increased beam depth and reduced span length is crucial for enhancing progressive collapse resistance.

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